WL-TR-97-8048

FILMLESS RADIOGRAPHY FOR AEROSPACE NDT

Timothy E. Kinsella
G. Richard Kahley

Liberty Technologies, Inc.
550 North Lane
Conshohocken, PA 19428-2208

December 1996

This is a Small Business Innovatin Research (SBIR) Phase I report.

Final Report For the Period 01 May 1996 - 31 December 1996

Approved for Public Release; Distribution is Unlimited.

Manufacturing Technology Directorate
Wright Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, Ohio 45433-7734

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASC/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Diana Carlin

DIANA CARLIN
Project Engineer
Non-Metals Branch
Processing & Fabrication Division

David R. Beeler

DAVID R. BEELER
Chief
Non-Metals Branch
Processing & Fabrication Division

Bruce Rasmussen

BRUCE A. RASMUSSEN, Chief
Processing & Fabrication Division
Manufacturing Technology Directorate

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify WL/MTPN, Bldg 653, 2977 P St., Suite 6, W-PAFB, OH 45433-7739 to help us maintain a current mailing list."

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1996	Final 05/01/96 - 12/31/96

4. TITLE AND SUBTITLE

Filmless Radiography for Aerospace NDT

5. FUNDING NUMBERS

C 41608-96-C-0791
PE 65502F

6. AUTHOR(S)

Timothy E. Kinsella
G. Richard Kahley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Liberty Technologies, Inc.
550 North Lane
Conshohocken, PA 19428-2208

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Wright Laboratory, Manufacturing Technology Directorate
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7739
POC: Diana Carlin, WL/MTPN, (937) 255-7277

10. SPONSORING/MONITORING AGENCY REP NUMBER

WL-TR-97-8048

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; Distribution is Unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT Report developed under SBIR contract

The purpose of this Phase I Small Business Innovation Research (SBIR) effort was to examine the suitability of an industrial system of filmless radiography to aerospace applications, and define such a system that would satisfy Air Force needs and requirements. Filmless radiography was applied to the nondestructive evaluation of Air Force aircraft demonstrating cost-effective benefits to routine inspections for foreign objects (FO), moisture entrapment, corrosion, and cracks. Film radiography has become a burdensome, inefficient, and expensive activity, especially in light of hazardous materials concerns. Hazardous materials handling is a significant environmental issue and therefore maintenance and disposition of film processing chemicals and the silver recovery program have become major concerns. Employment of a system of filmless radiography would not only reduce the cost of dealing with hazardous materials, but eliminate it completely.

14. SUBJECT TERMS SBIR Report

Nondestructive Evaluation (NDE), Aircraft, Radiography, Materials.

15. NUMBER OF PAGES 32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASS OF THIS PAGE.	19. SECURITY CLASS OF ABSTRACT	20. LIMITATION ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z239-18
298-102

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SUMMARY

The Purpose of this Phase I effort was to examine the suitability of an industrial system of filmless radiography to aerospace applications, and define such a system that would satisfy Air Force needs and requirements. Filmless radiography was applied to the nondestructive evaluation of Air Force aircraft demonstrating cost-effective benefits to routine inspections for foreign objects (FO), moisture entrapment, corrosion, and cracks. Film radiography has become a burdensome, inefficient, and expensive activity, especially in light of hazardous materials concerns. Hazardous materials handling is a significant environmental issue and therefore maintenance and disposition of film processing chemicals and the silver recovery program have become major concerns. Employment of a system of filmless radiography would not only reduce the cost of dealing with hazardous materials, but eliminate it completely.

An industrial system of digital radiography is currently available, and was used to experimentally study the feasibility of non-film (phosphor) imaging in Air Force depot and field environments. Liberty Technologies' RADView system of filmless radiography was originally designed for the industrial market of nuclear and conventional utilities. This system was taken into the Air Force environment for evaluation in order to develop the definition of a similar system suitable to Air Force/aerospace needs, define the efforts necessary to develop, produce, and implement such a system.

Field tests were conducted at depots (WR-ALC and SA-ALC), and operational field environments (Tyndal AFB, Randolph AFB, and Langley AFB). While the emphasis of the evaluation was on the F-15, some work was also accomplished relative to the inspection needs of the C-141 and T-38. Current phosphor (filmless) technology permits inspections for FO, moisture entrapment, and corrosion comparable to that achievable with conventional film. Examination of T-38 and C-141 structures for cracks revealed that while the phosphor screens are capable of detecting some cracks, they did not do as well as conventional film. While it was acknowledged that phosphor image quality must improve in order to provide a comparable

inspection for cracks, a quantitative comparison of this capability is extremely difficult and needs further attention.

The project developed both characteristic and exposure curves for x-ray energies in the 50kv to 160kv range and revealed the potential associated with slightly longer exposures at reduced PMT voltage. It also demonstrated the beneficial use of filters at the tube, and a higher sensitivity to scattered radiation than exhibited by conventional film.

In order to assess the economic benefits of filmless radiography, film usage at several F-15 units was examined. Records and estimates of film usage at the various F-15 organizations varied from a low of $80,000 per year to a high of more than $200,000 per year. While this range represents a variety of combinations of aircraft age, utilization rates, etc., it indicates that a system of filmless radiography must cost less than $200,000 in order to achieve a return-on-investment of one to two years.

It was found that the system is capable of performing acceptable inspections for Foreign Object Debris (FOD), moisture entrapment, corrosion, and some cracks. Although this represents approximately 80-85% of most routine aircraft inspections, widespread acceptance will require the capability of producing 2% EPS (equivalent penetrameter sensitivity) over the range of materials and thicknesses typical of airframe structures, a 14"x17" image format, and increased throughput which is currently limited by eraser efficiency.

1.0 INTRODUCTION

The goals of the "Filmless Radiography for Aerospace NDT" Phase I SBIR program include 1) demonstration of available technology, 2) definition of an Air Force suitable system and the efforts needed to develop, produce, and implement such a system, and 3) development of an economic justification for filmless radiography.

1.1 Scope and Objectives.

This project is a demonstration effort on the benefits of filmless radiography to aerospace applications. Due to the large scope of potential aerospace applications and the limited resources available to this Phase I effort, the Air Force NDI IPT Team recommended that the effort focus on F-15 structural inspections at both depot and operational locations.

1.2 Filmless Radiography.

The history of storage phosphors can be traced back to the early part of this century, though practical uses of the technology were not recognized until the early 1970's. Kodak was the first to patent the general concept of storage phosphor use for a variety of radiographic imaging applications. Though Kodak continued the internal development of the technology, it was beaten to the market when in 1982, Fuji Photo Film of Japan introduced the first commercial phosphor technology (referred to specifically as Computed Radiography, or CR) for medical imaging. Both the Kodak and Fuji approaches are based on a europium-doped barium fluorobromide (BaFBr:Eu) phosphor, which requires a PSL (photo-stimulated luminescence) laser wavelength of approximately 630 nm and exhibits a luminescence wavelength of approximately 375 nm. During the early 1990's another US company, Molecular Dynamics, introduced a CR system for imaging biological materials (tissue sections as well as molecules). The Molecular Dynamics system is also based on the Fuji phosphor, though they employ plates manufactured by Kodak.

Liberty Technologies' RADView system of industrial filmless radiography employs an approach that is based on a rare-earth doped alkaline-earth sulfide phosphor technology.

The approach employed by the RADView system utilizes a thin plastic substrate coated with storage phosphor material. The coating consists of phosphor particles of a specific size adhered together and to the substrate by an organic binder. This produces screens that are rugged, flexible and are physically handled the same way as film for exposure. Upon exposure of the screen to radiation, a population of trapped electrons is created in the storage phosphor layer to produce a latent image. This is analogous to film, which when exposed to radiation, will store a latent image that is later chemically developed. However, in the case of the storage phosphor screens, the latent image is read optically without chemical processing.

Optical readout is accomplished by scanning the screen with a focused laser beam which causes the storage phosphor screen to luminescence. The amount of luminescence that is produced from each resolution element on the screen is directly proportional to the prior radiation exposure. By measuring the amount of luminescence with a photo-detector, the information can be easily digitized and stored. Thus, for each resolution element on the storage phosphor screen, a corresponding digital intensity signal is stored. This information is then digitally reconstructed and displayed on a monitor for viewing. Also, when the storage phosphor is scanned, the information is subsequently erased, so that the screen can be re-used many times.

The specific storage phosphor material being employed in Liberty's imaging screens is a strontium sulfide (SrS) crystalline material doped with trace amounts of rare-earth ions, cerium (Ce^{3+}) and samarium (Sm^{3+}). When the rare-earth ions Ce^{3+} and Sm^{3+} are introduced within the SrS crystal, the energy level configurations change. This allows certain types of interaction between the ions and the SrS crystal, as well as between the two ions, shown schematically in Figure 1. First, it can be seen that when the SrS crystal is exposed to ionizing radiation, electrons from its valence band are excited to its conduction band leaving behind a positive charge, or *hole*. When the electron and hole eventually recombine, their stored energy is transferred to the Ce^{3+} ion resulting in the excitation of the Ce^{3+} ion's 4f ground state electron to

its 5d state. Once in the 5d state, the electron can tunnel to a neighboring Sm^{3+} ion where it becomes trapped. This trapping process constitutes the latent image formation within the phosphor layer. Noting that the layer has a large number of trapping sites, a great deal of radiation energy can be absorbed before all possible Sm^{3+} sites are filled.

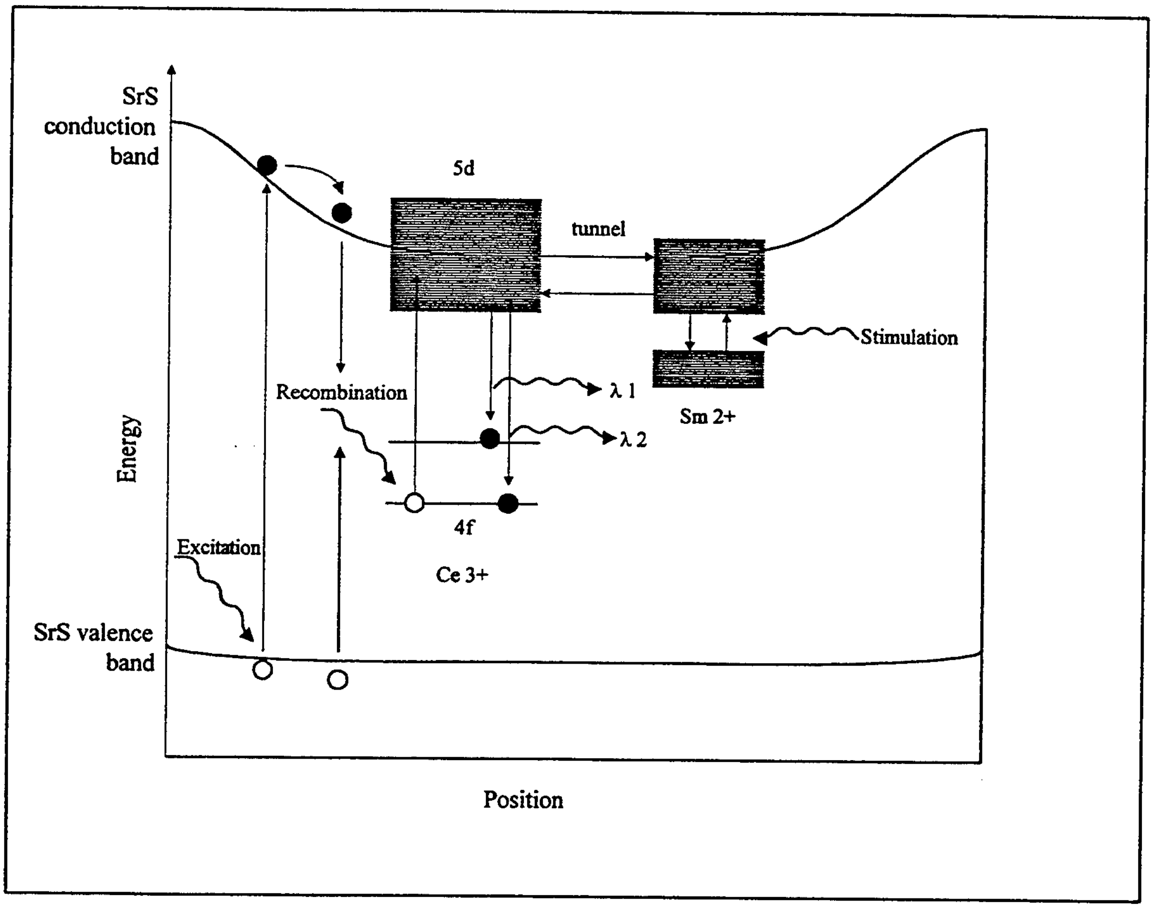


Figure 1. Energy band diagram for SrS:Ce, Sm.

The electron trapping process is somewhat analogous to the initial process occurring in silver halide grains exposed to photons; the latent image creation process consists of creating a population of trapped electrons in the storage phosphor imaging screen. However, the trapping of electrons at Sm sites does not induce a permanent chemical change, but a simple reversible change in the valences of the two rare-earth ions. The process can be reversed by stimulating

trapped electrons with external energy. Once promoted to its excited state, the electron can tunnel back to its Ce^{4+} neighbor, where it can relax to produce luminescence, or more correctly, *photostimulated luminescence* (PSL). The intensity of the PSL is directly proportional to the number of trapped electrons, which is in turn proportional to the amount of radiation energy absorbed by the storage phosphor screen. It should also be noted that the transition times involved in producing PSL are fast, typically about 100 nanoseconds (1/e time constant). By comparison, the phosphor employed by other CR systems is about 10 times slower. This allows for much faster readout times with Liberty's approach, in particular at high scan resolutions.

The storage phosphor screens absorb and subsequently re-radiate energy in a linear fashion. However, for the process to be practical for radiographic imaging, a method is required to convert the visible luminescence pattern emitted by the storage phosphor screen to a permanent and easily viewable format. The way that this is accomplished is shown schematically in Figure 2. First, the storage phosphor screen is scanned with a 1 μm laser beam so that only a small volume of the phosphor layer is actually photostimulated, with the remaining areas undisturbed. The scanning mirror is digitally controlled so the precise laser beam position on the screen is always known.

The PSL intensity from the small phosphor area is then collected and propagated to a light sensor, called a photomultiplier tube (PMT). The PMT converts the incident luminescence photons to photo-electrons (current) and amplifies the amplitude of the photo-current. This current is then converted to a voltage and digitized. The digital voltage value is stored in computer memory as a function of the *x-y* coordinates on the phosphor screen from which the PSL was initially measured. This process is repeated until every point on the phosphor screen has been scanned, and the image is computed and digitally displayed. After the image has be computed, a residual latent image usually remains on the screen, and must be remove prior to re-use.

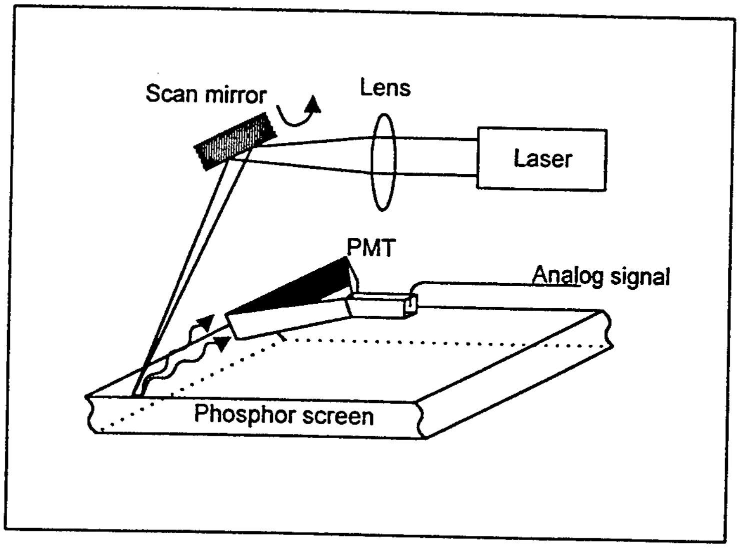


Figure 2. Readout and digitization process for creating a radiographic image

In order for such a system to effectively replace film, it must go where film goes and do what film does. That is, the phosphor screens must be flexible; the system as a whole must be portable, or at least mobile; and it must have the resolution/sensitivity of film and produce images utilizing 12 bits of data. In practice, the use of such a system will consist of 1) exposing the screen, 2) scanning the screen and acquiring an image, 3) analyzing the image on a workstation, and 4) erasing and re-exposing the screen as shown in Figure 3 below.

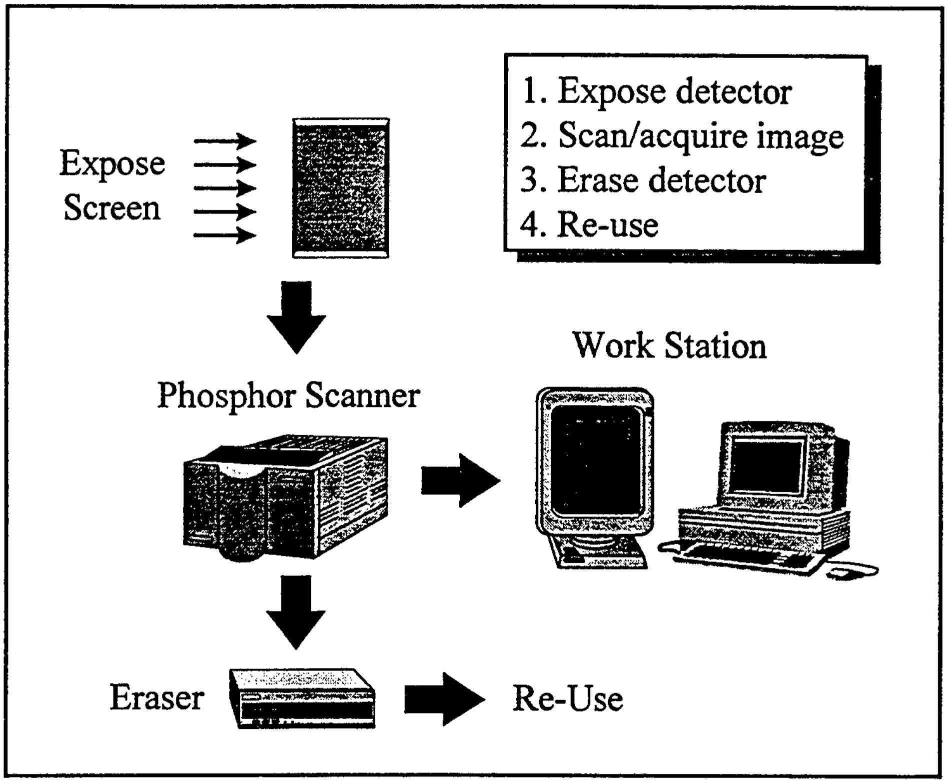


Figure 3. Block Diagram of a Filmless Radiography System.

2.0 FIELD TESTS

In order to assess how well the currently available system meets these needs, a series of field tests were conducted. The system is, in fact, mobile and was easily transportable from one location to another. Figure 4 illustrates the system (less the eraser) as it was located at Kelly AFB in San Antonio, TX. Transporting the system consisted of packing it in cases and shipping it over conventional land transportation.

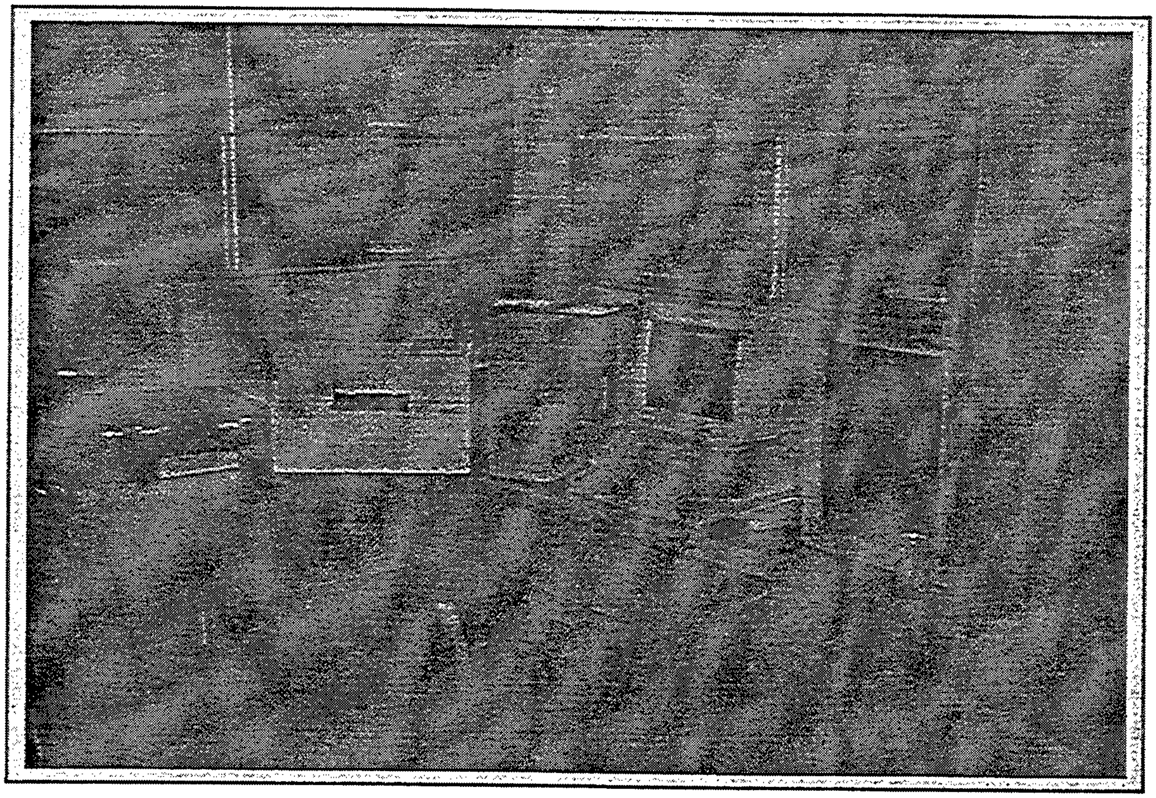


Figure 4. RADView System at SA-ALC

2.1 F-15 Inspection Overview.

The F-15 NDI manual (T.O. 1F-15A-36) was reviewed to assess the number and type of radiographic inspections that are routinely performed on an F-15 aircraft. It is recognized that the -36 is not comprehensive (it does not include TCTO's or many depot inspections. However, since its content is based on field experience, durability test data, or engineering predictions, there is basis for using it, in general terms, as an inspection model. A summary of this review is given in Table 1.

Part/Assembly	Defect/Conditon	# Exp.	# Film	Size	Film Typ
Torque Box Main Spar	Fatigue Cracks	2	2	7x17	AA or M
Wing Tip Assy.	Water Entrapment	4	11	14x17	D7
Wing Tip Assy.	Foam Adhesive Separation	11	13	7x17	D7
Wing Tip Closure Rib	Fatigue Cracks	9	9	7x17	D7
Wing Tip Fwd. Spar	Fatigue Cracks	1	2	7x17	AA/M
Flap Assy.	Water Entrapment	5	15	14x17	D7
Flap Assy.	Foam Adhesive Separation	20	20	7x17	D7
Aileron Assy.	Water Entrapment	3	12	14x17	D7
Aileron Assy.	Foam Adhesive Separation	14	14	7x17	D7
Intermediate and Main Spars	Distortion or Breaks	3	3	14x17	M
Outbd. T.E. Ribs	Fatigue Cracks	4	4	7x17	AA
		1	1	14x17	AA
Outbd. Torque Box Ribs	Fatigue Cracks	3	12	7x17	AA/M
		1	2	7x17	AA/M
Stabilator Outbd. L.E. Box	Water Ent/Foam Adh. Sep.	5	9	14x17	D7
Stabilator Torque Box	Water Entrapment	3	13	14x17	AA
Stabilator Torque Box	Foam Adhesive Separation	26	26	7x17	AA
Stabilator Aft Box	Water Entrapment	4	19	14x17	D7
Stabilator Aft Box	Foam Adhesive Separation	14	17	7x17	D7
Stabilator Tip	Water Ent/Foam Adh. Sep.	1	3	14x17	D7
Rudder	Water Ent/Foam Adh. Sep.	4	9	14x17	D4
		1	2	14x17	D4/D7
Var. Inlet Ramp, Inbd. Panel	Water Entrapment	1	2	14x17	AA/M
Var. Inlet Ramp, Rib Support	Cracks	2	4	14x17	M
Var. Inlet Ramp, Inbd. Panel	Skin to Core Bond	2	4	14x17	D7
Var. Inlet Ramp, Outbd. Panel	Water Entrapment	3	3	14x17	D7
Var. Inlet Ramp Assy.	FOD	12	25	14x17	AA
		2	8	14x17	AA/M
No.1 Var. Inlet Ramp Assy.	FOD	4	7	14x17	AA
		4	10	7x17	AA
Var. Inlet Ramp, Outbd Panel	Skin to Core Bond	1	1	14x17	D7
Var. Inlet Ramp, Outbd Panel	Skin to Core Bond	1	1	14x17	D7
Composite Speed Brake	Cracks in Adhesive	8	16	7x17	D7/D4
Composite Speed Brake	Water Entrapment	28	28	14x17	AA
		4	4	7x17	AA
Vertical Stab., Fwd. Box	Water Entrapment	4	13	14x17	D7
Vertical Stab. Torque Box	Water / Closure Cracks	1	2	14x17	AA
Vertical Stab. Torque Box	Foam Adhesive Separation	28	28	7x17	AA
Vertical Stab. Aft Lwr. Box	Water Entrapment	1	5	14x17	D7
Vertical Stab. Aft Lwr. Box	Foam Adhesive Separation	1	1	7x17	D4
		4	4	7x17	D7
Fairing Assy.	Water / Foam Adh. Sep.	2	4	14x17	D7/D4
		252	388		

Table 1. T.O. 1F-15A-36 RT Inspections

This review of the F-15 NDI manual revealed the following:

a. Radiographic inspection procedures are included for a total of 35 parts/assemblies. All of the following numbers should be doubled to consider the entire aircraft since only the left side is shown. The defects/conditions sought in these inspections include water entrapment, foam adhesive separation, FOD, and cracks.

b. Those 35 procedures employ 252 exposures and 388 pieces of film. Of that film total, 23 are double loaded and 113 involve multiple films exposed with single exposures in various configurations. Of the 388 films required, 200 (approx. 51%) are 14"x17" and 188 (48%) are 7"x17" in size.

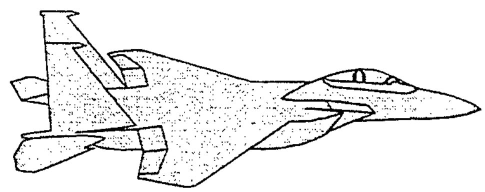
c. Of the 252 exposures:

- 24% are for water entrapment
- 47% are for foam adhesive separation
- 5% look for both water entrapment and foam adhesive separation
- 14% are for cracks (includes distortion, breaks, foam cracks, etc.)
- 9% are for FOD
- Two exposures are employed as backup technique for inspection of skin-to-core bond.

d. Of all these procedures, the use of penetrameters was specified only for one inspection of the wing tip closure rib, and for one of the two backup inspections for skin-to-core bond on the variable inlet ramp outboard panel. The use of penetrameters was questionable in five other techniques, where the procedure said to locate penetrameters in accordance with a figure, but they are not shown on the figure, nor are they called out in the equipment list.

As with most aircraft, the F-15 receives a phase inspection after a specified interval of flight hours. Examination of the F-15's inspection requirements manual (T.O. 1F-15A-6) revealed that

the F-15's inspection interval is 200 hours as shown in Figure 5. Every 200 hours the vertical and horizontal stabilizers, flaps and ailerons are inspected. Every 400 flight hours inspection of the ramp ribs, closure ribs, wing spars, and ramps are added to the 200 hr. phase inspection. Every 1200 flight hours inspection of the wing tips, horizontal stabilizer tips, inboard/outboard ramps, speed brake and rudder are added to the 200 hr. and 400 hr. inspections.



200 hr	400 hr	1200 hr
Vertical Stab.	Vertical Stab.	Vertical Stab.
Horizontal Stab.	Horizontal Stab.	Horizontal Stab.
Flaps	Flaps	Flaps
Ailerons	Ailerons	Ailerons
	Ramp Ribs	Ramp Ribs
	Closure Ribs	Closure Ribs
	Wing Spars	Wing Spars
	Ramps	Ramps
		Wing Tips
		Horizontal Stab. Tips
		Inbd/Outbd Ramps
		Speed Brake
		Rudder

Figure 5. F-15 Periodic Radiography Inspections

2.2 Depot vs. Operational Environments

Depot and operational organizations perform fundamentally different functions, yet also exhibit some similarities in the specific inspections they perform as shown in Figure 6. Depots are

essentially manufacturing, repair, end engineering organizations that also provide laboratory services. Depots are responsible for all engineering and management functions associated with complete weapon systems, such as the F-15, once they are initially delivered from the contractor.

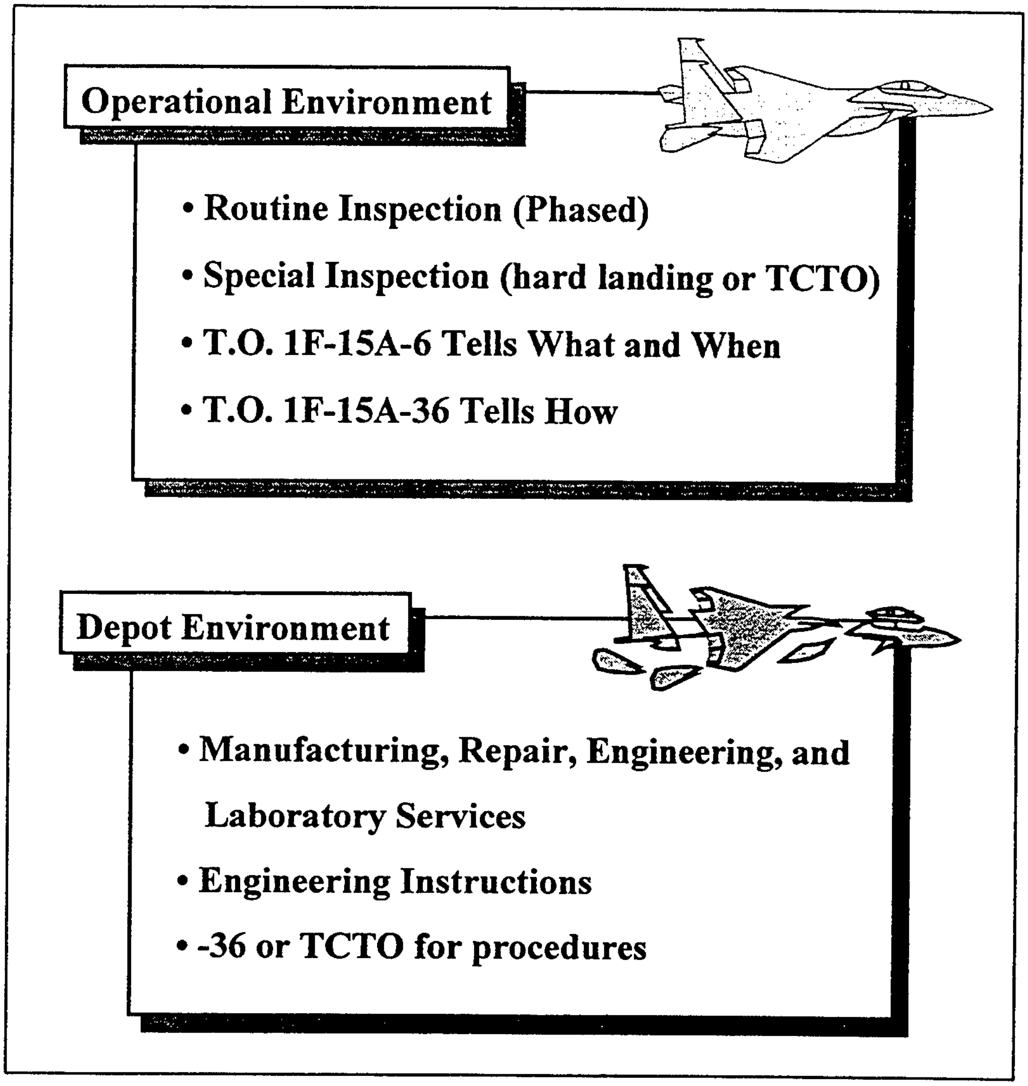


Figure 6. Operational vs. Depot Environments

Aircraft are periodically returned to the depot (typically once in 6 years) for major overall, maintenance, upgrades, etc. This work will usually include both routine inspections from the -36, as well as nonstandard inspections directed by engineering instructions or Time Compliance Technical orders (TCTO's). Depot engineering organizations also develop and/or approve the NDI procedures and equipment used by other organizations that support or use their aircraft.

Operational organizations, on the other hand, have the primary responsibility of performing the day to day maintenance and inspections required to generate sorties. They perform NDI inspections when specified in the -6 and in the manner specified in the -36.

2.2 Results

In the case of the F-15 inspections, phosphor images were obtained on actual parts or assemblies that were being routinely inspected. The FOD images of the inlet ramp, one of which is shown in Figure 7, were obtained from an inlet that had been removed from the aircraft and was inspected in the NDI shop. The phosphor images detected the same FO that was detected with the film technique. This inspection was performed both at WR-ALC and at Tyndal AFB. The inspection at Tyndal AFB was conducted in a flight line hangar (actually the paint barn) to demonstrate that the phosphor screens were able to be used in the same environment as film.

The screens were carried back to the NDI lab, which was nearby, for digitization. However, it would have been possible to perform the entire process (exposure, digitization, and viewing) in the hangar as long as ac power was available. One conclusion from this test was that 14"x17" screens would be necessary to make the process efficient. In general, acceptable images with the phosphor screens required half the exposure time and approximately 80% of the energy (i.e. lower kv) required for conventional film. The wide latitude of the phosphor screens allowed many exposures to be done with a single screen and exposure, as opposed to the conventional technique that required double loading with two speeds of film.

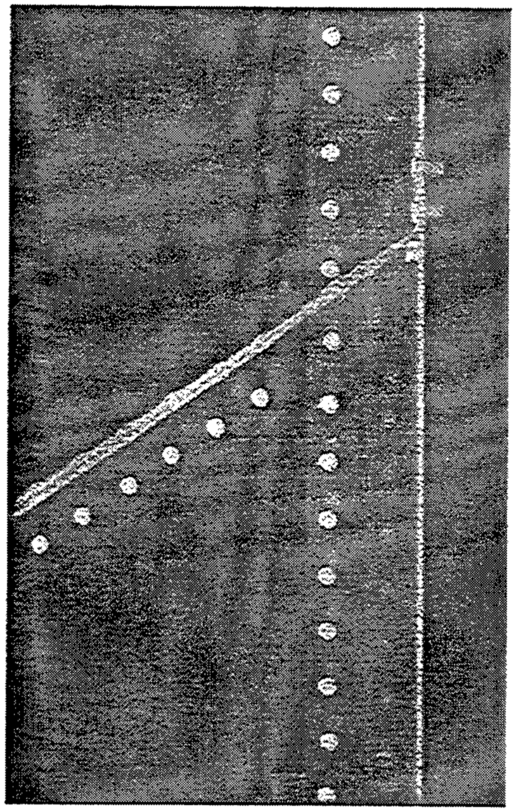


Figure 7. Inlet Ramp FOD

The F-15 rudder examination that detected moisture entrapment in the honeycomb was also conducted at WR-ALC. The rudders are typically removed from the aircraft and examined with the real time radiography system. The rudders were examined and areas of interest were identified, which were then examined with the phosphor system. The phosphor images, an example of which is shown in Figure 8, were comparable to the real time images. This effort also identified the desire to capture individual frames from the real time system and store them digitally in RADView. This would preclude the need to retain large volumes of videotape that contained unnecessary information.

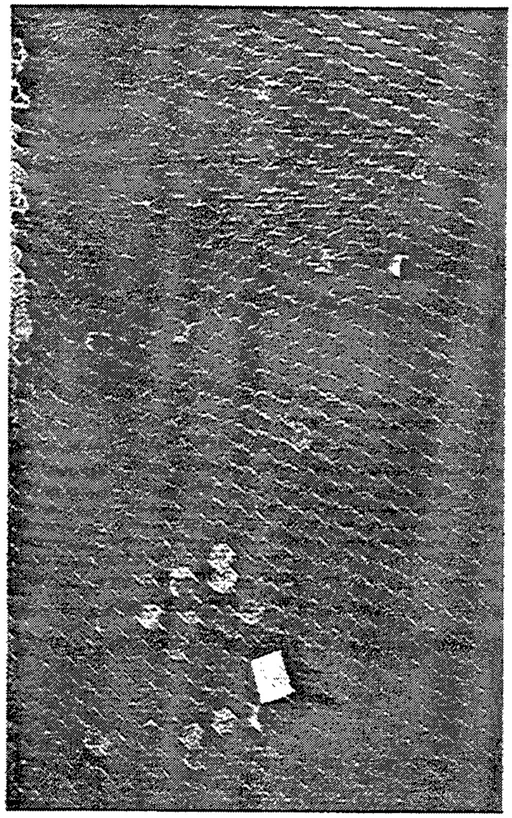


Figure 8. Moisture Entrapment in Honeycomb Rudder

Detection of corrosion was another of the specific flaws evaluated. Again, F-15's were the subject, this time at Langley AFB, VA. Examination with the filmless radiography system was conducted after inspections with conventional film radiography. The phosphor images easily detected the corrosion, as shown in Figure 9, and were deemed comparable to the film images. Unfortunately, there was no opportunity to further examine these particular ailerons to determine the actual extent of corrosion/skin thinning and hence quantify the system's performance.

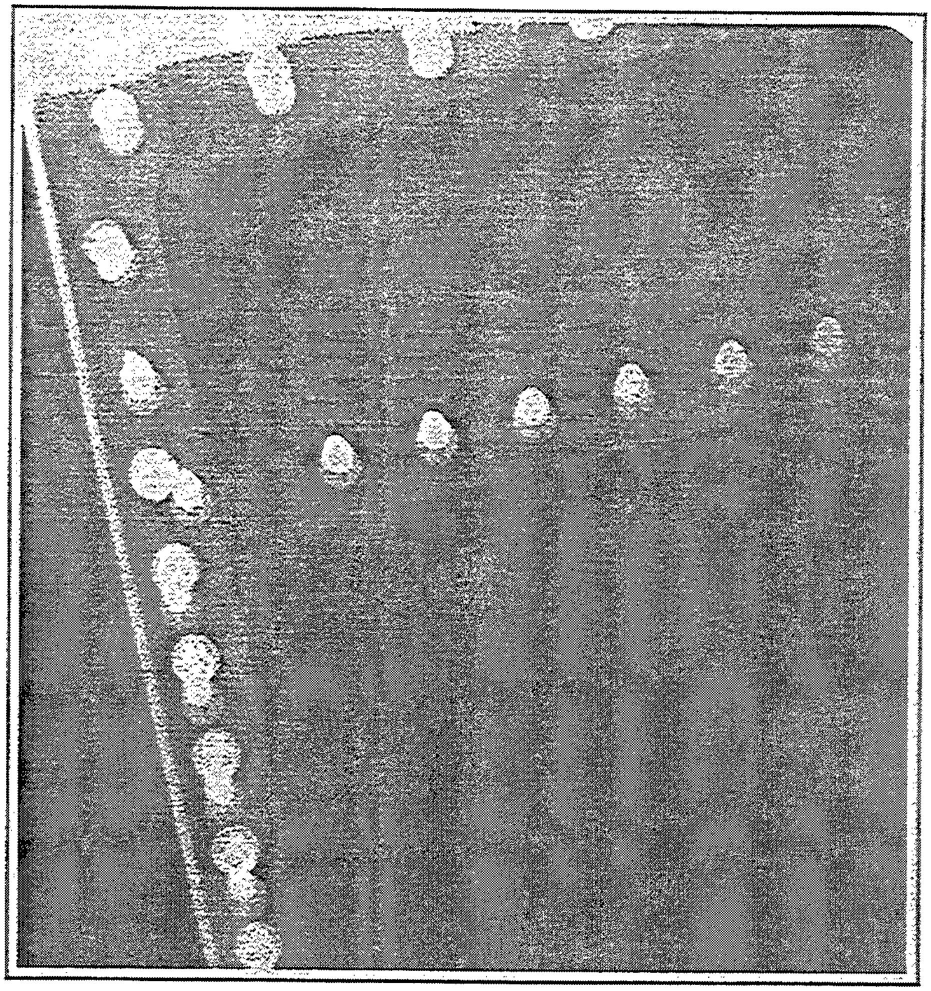


Figure 9. Corrosion in F-15 Wing Skin

Randolph AFB, TX was visited for examination of T-38 aircraft which also require considerable radiography. Of particular interest at this location was demonstration of the flexibility of the phosphor screens and cassettes. One typical inspection is of a frame several feet back from the leading edge of the inlet. Film is placed on the inside skin and exposed from the outside. This inlet is quite small (less than 18" high) and placement of the film cannot easily be performed by hand. Therefore, local technicians developed a tool consisting of a styrofoam plug, as shown in Figure 10, that just fit the inside contour of the inlet to which the film can be taped and the plug as a whole moved down to the appropriate location. Since the magnetic bars that close the end of the paper cassette are attached by velcro, they were simply removed and the end secured with masking tape thereby making the entire cassette flexible. The phosphor screen was successfully

located and exposed in the same manner as film. Since this was not the intent of the original cassette, a more effective design should be subsequently developed.

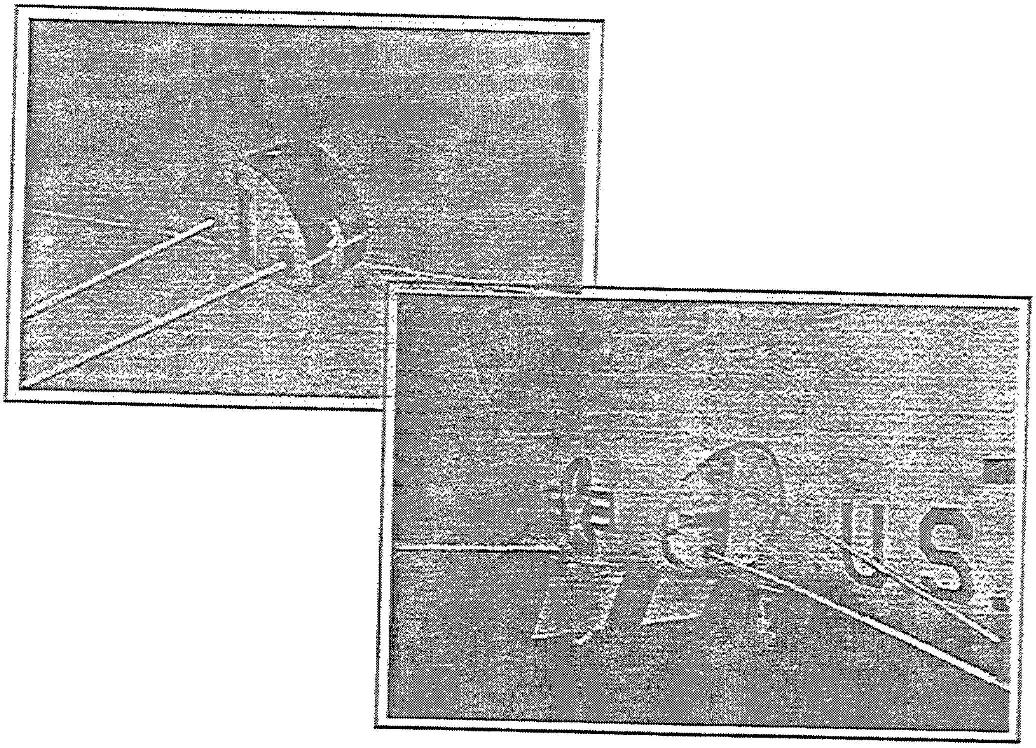


Figure 10. T-38 Inlet Film Placement

Figure 11 shows both film and phosphor images of the T-38 inlet. This area is frequently looked at for cracks in the bulkheads/frames. This figure illustrates the much wider latitude possible with phosphor. Conventional film techniques for examination of this area require multiple exposures with different speeds of film due to the large number of systems (wiring, tubing, brackets, etc.) that pass through this area. The use of phosphor technology would greatly reduce the number of exposures required for a complete examination.

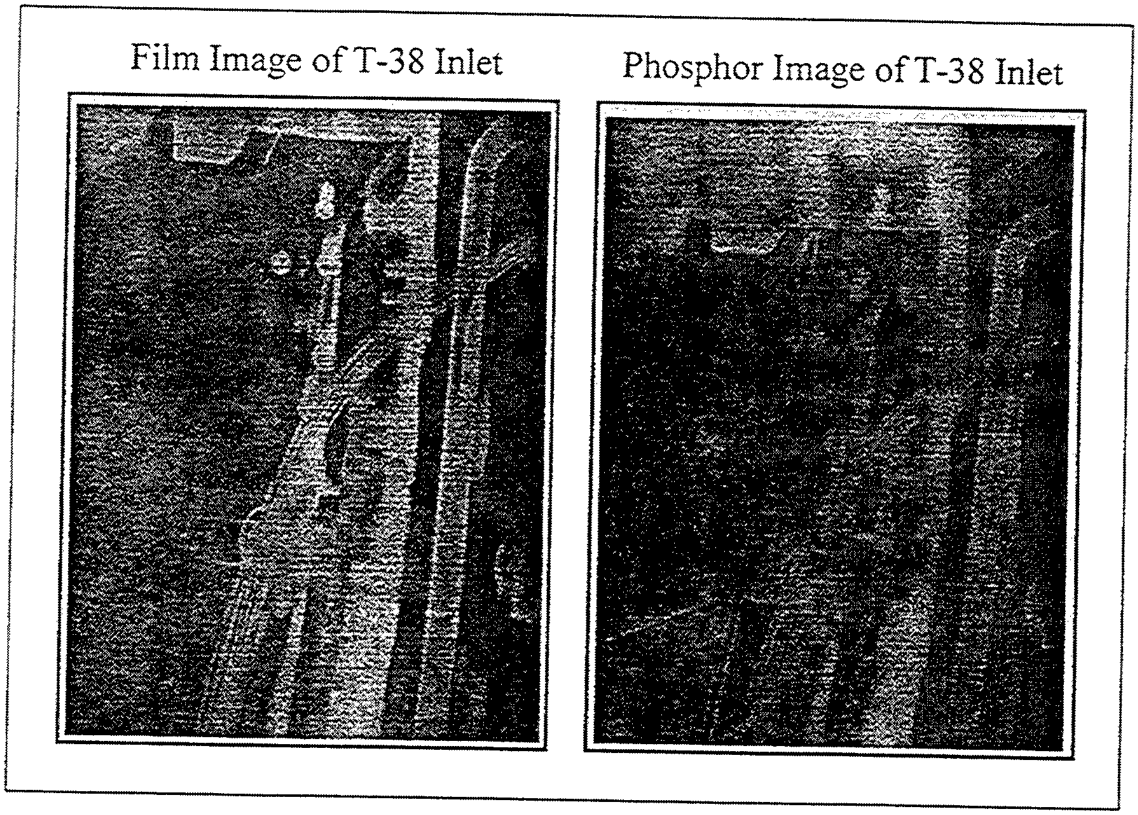


Figure 11. T-38 Inlet Inspection

Examination of T-38 and C-141 structures for cracks revealed that while the phosphor screens are capable of detecting some cracks, it did not do as well as conventional film. While it was acknowledged that phosphor image quality must improve in order to provide a comparable inspection for cracks, a quantitative comparison of this capability is extremely difficult. Simply comparing images is unacceptable because of the subjective nature of the comparison and the extreme sensitivity to small geometric changes. To illustrate this, a film image of a C-141 wing splice revealed a crack extending completely between two fasteners. A phosphor image of the same area showed the same crack, although not the complete length, but also revealed a smaller crack originating from an adjacent hole that was not picked up by the film. Recreating exactly the same geometry is very difficult, nor is it possible to simultaneously expose film and phosphor because comparable images would require different exposures. An acceptable quantifiable characteristic needs to be identified and used for comparison, such as resolution in Lp/mm (line pairs per millimeter), system MTF, square wave response (SWR), characteristic curve slope, etc.

3.0 SYSTEM PERFORMANCE

Initial system characteristic curves for x-ray energies were developed. These curves are illustrated in Figure 12 and verify that they are indeed a linear function on a logarithmic scale as predicted. It should be noted that the phosphor screens reach saturation (4.0 phosphor density, or PD) with x-ray energies at a much lower exposure than with gamma energies. Longer exposures can be obtained with the same screen, if desired, in one of two ways. The first is by employing a lead intensifying screen which, at these low energies produce little or no intensifying action, and serve more as a shield. As can be seen in Figure 12, this results in a lower characteristic curve which permits a longer exposure before reaching a saturation density of 4.0 PD. The second way of achieving this same result is by reducing the photomultiplier tube (PMT) voltage. This produces a lower current from the PMT for a given amount of PSL, or visible light. The result again, is a lowering of the characteristic curve permitting a longer exposure before reaching saturation.

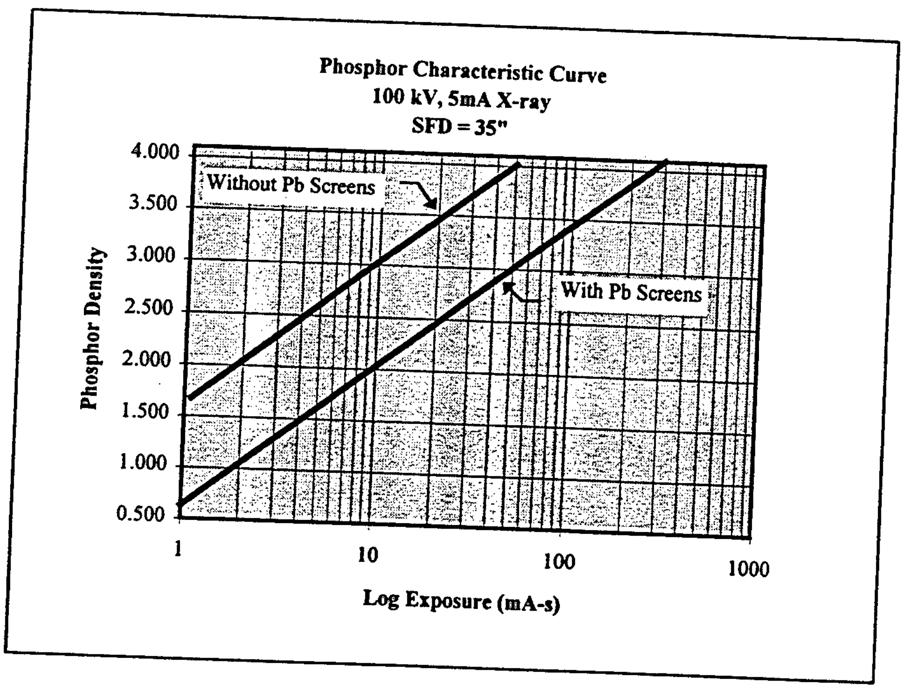


Figure 12. System Characteristic Curve

An exposure curve was developed for aluminum up to 2" as shown in Figure 13. What is significant about phosphor screens is that this curve is relatively shallow, requiring a significant change in exposure to produce a large change in density. What this means is that the system is very forgiving. Because of the steep slope of the usable portion of film characteristic curves, there is a very narrow range of exposures that will produce an acceptable image. In contrast, because of the shape of the characteristic and exposure curves, phosphor technology provides a very effective system which can examine a wide range of material thickness in a single image, and yet produce an acceptable image over a relatively wide range of exposures.

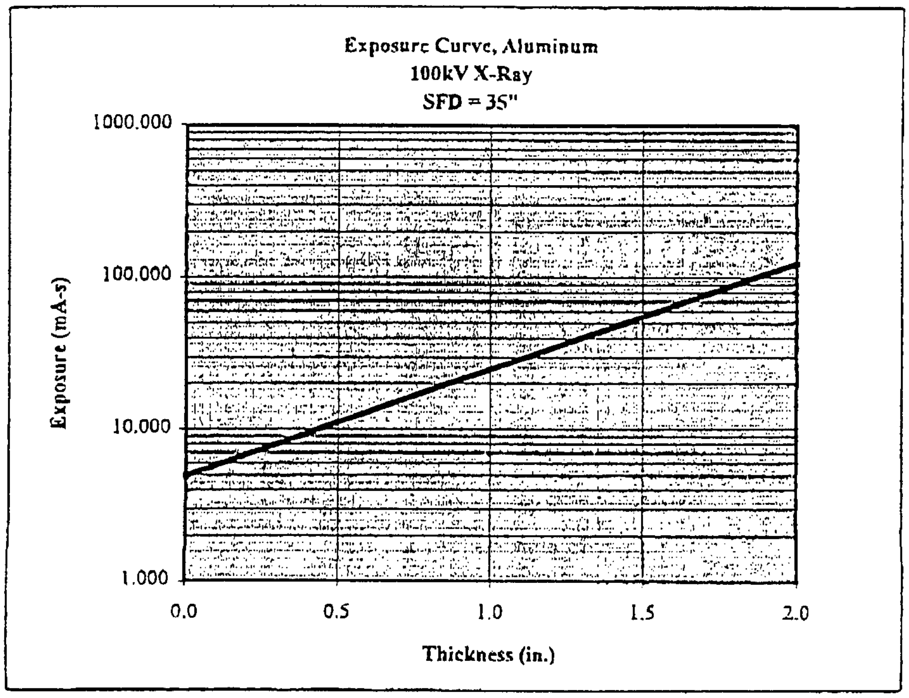


Figure 13. Exposure Curve

An initial attempt was made to quantitatively compare phosphor and film resolution. Digital spatial resolution (DSR) is a measure of the smallest piece of detectable information, or the pixel size. It can be expressed in either microns (mm) or one millionth of a meter, dots per inch (dpi), line pairs per millimeter (LP/mm), or mils (thousandths of an inch). Conversion factors for these various measurements is shown below.

1μm	= 0.0000394"	= ~ 0.04	mils
100μm	= 0.00394"	= ~ 4	mils
1mm	= 0.0394"	= ~ 40	mils

2 lp/mm	= 250 μm	(~10 mils)	= 102 dpi
5 lp/mm	= 100 μm	(~ 4 mils)	= 254 dpi
6 lp/mm	= 83.25μm	(~ 3.3 mils)	= 305 dpi
7 lp/mm	= 71.34μm	(~ 2.8 mils)	= 356 dpi
12 lp/mm	= 41.62μm	(~ 1.5 mils)	= 610 dpi

To make these measurements a test object, or resolution pattern, is taken consisting of a series of regularly-spaced bars and spaces (the bars being assumed to absorb x-rays), as shown in Figure 14. A perfect x-ray image of this test object would produce a square wave density distribution. In practice however, the edges are blurred. The density difference between bar and space in the image is called the image contrast, and the fineness of the pattern is the spatial frequency (in Lp/mm). If a series of bar/space patterns of different spatial frequencies is taken, a point will be reached where the system is incapable of resolving the pattern.

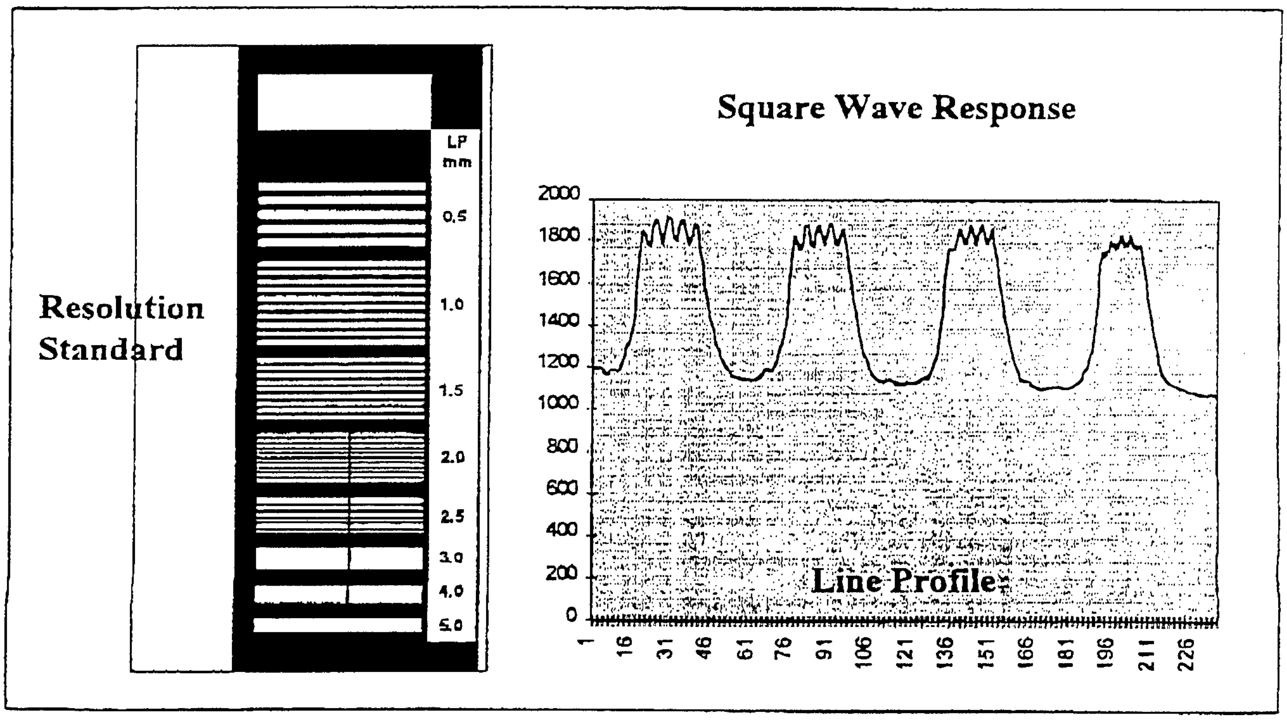


Figure 14. Resolution Measurement

The square wave response (SWR) shown in Figure 14 is one method on measuring of measuring the density difference for a series of five bar/space pairs. If SWR is plotted against the spatial frequency, a curve representing the modulation transfer function (MTF) is obtained as shown in Figure 15. This figure is a composite of data from a number of screens and films, and illustrates relative MTF functions for a series of four phosphor conditions and Kodak AA film.

Figure 15, although a composite, illustrates several important points. First, it is important to note that the film data was taken from a conventional image that was digitized. The film and phosphor exposures were the same for comparison's sake, but resulted in a film image that was too light. Therefore, the MTF curve for film should be a bit higher which would make it roughly

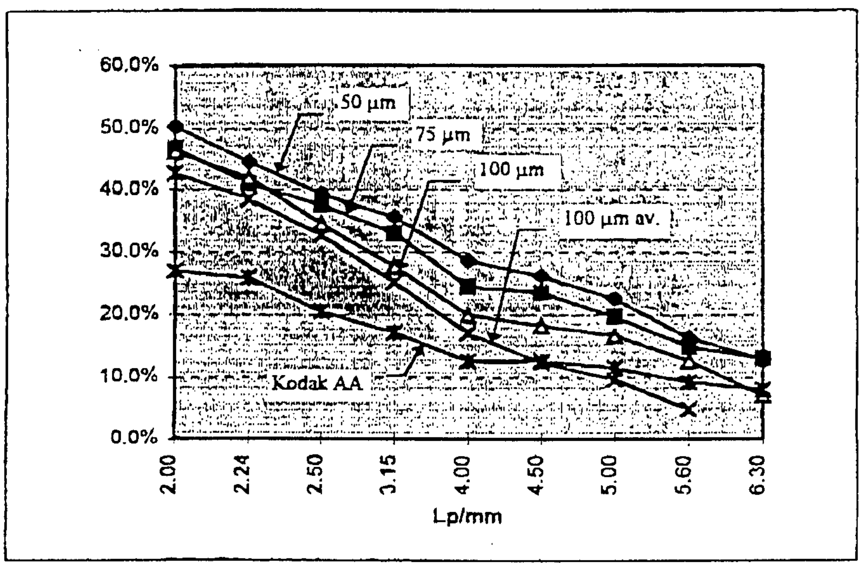


Figure 15. Film vs. Phosphor MTF

comparable to the phosphor. The laser used in the phosphor scanner has a constant spot size of 50μm (0.002"). Pixel size can be varied by sampling data points every 50μm, 75μm, 100μm, or averaging 50μm data points to obtain a 100μm pixel. Since SWR is a measure of the definition of the bars/spaces, it makes sense that this resolution indicator improves with smaller and smaller pixel sizes. As with all NDT applications however, there is a penalty associated with this greater resolution and that is a much greater volume of data for a given image. These measurements are

a promising method of quantifying both film and phosphor capability, and will require additional work to establish meaningful and useful measurement techniques.

The acceptability of a film image is usually judged by the optical density (OD) in the area of interest. This is difficult to do in the same way with phosphor images because phosphor density (PD) is a measure of the intensity of emitted PSL which is digitized to 12bits. Since optical density is a measure of transmitted intensity and phosphor density is a measure of emitted intensity, there is no meaningful direct conversion. PSL is digitized in levels from 0 to 4096 and is converted to 0.0 to 4.0 PD which is only coincidentally similar to 0.0 to 4.0 OD.

If a screen is digitized after the erasure process, it can be seen that a certain amount of density remains. This is similar to the fog level of film and the term will be used here to refer to remaining density after erasure. Experiments have shown that changes in exposure do not measurably effect the density distribution of a test object. Varying the exposure only moves the distribution up or down the density scale (another illustration of the forgiving nature of the technology). An acceptable image then, can be defined as one in which the lower densities of the test object density distribution do not overlap those of the fog level, and the highest densities of the test object density distribution do not approach the A/D saturation level (4.0 PD). This is illustrated in Figure 16.

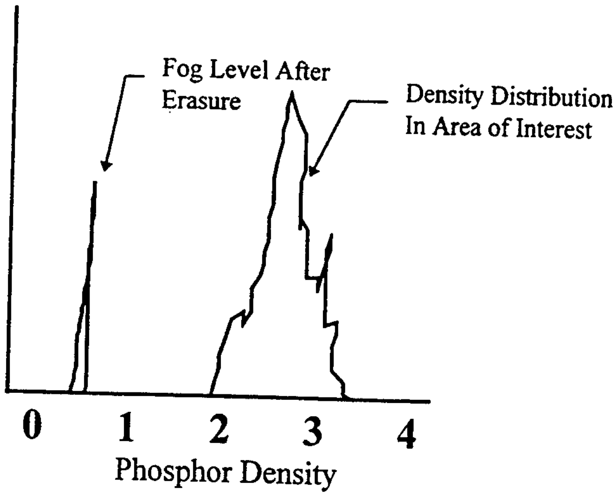


Figure 16. Technique Evaluation

Comparing these tests with earlier evaluations of the technology with gamma radiation indicate that the phosphor reacts more readily with the lower x-ray energies. That is, more sites are excited per input quanta of energy, and hence the A/D is saturated more quickly. From this it can be inferred that the phosphor will also be more sensitive to scattered radiation and further, that filtering of the broad spectrum of energy put out by an x-ray tube will improve the image quality. Experiments using additional lead shielding and a lead filter at the tube port confirmed a qualitative improvement. Further work must be done to better quantify these affects and develop procedures accordingly.

One final applications observation. An erased screen must exhibit a low fog level with a narrow density distribution (i.e. previous latent or "ghost" image eradicated. The current eraser uses a combination of sodium and IR lamps to achieve this. The sodium vapor lamp provides radiation at a wavelength that discharges phosphor screens; however the commercially available lamps currently used also emit radiation which charges up the phosphor screen. These simultaneous effects result in a consistent, uniform density distribution across the screen, but leaves the screen at a density that is potentially high enough to interfere with the low densities of the subsequent image. The IR lamp then is used to reduce this narrow fog level to a sufficiently low mean density, usually well below 1.0 PD. Subsequent development work needs to establish a generally

accepted definition of adequate erasure; e.g., a mean density less than 0.8 PD with a density distribution not to exceed 0.3 PD.

During shipment to one of the field locations, the IR lamp in the eraser was damaged beyond repair. This meant that erasure could be done with the sodium lamp alone, resulting in an acceptably narrow, but one that remained around 2.0 PD. After some consideration it was decided to lower the PMT voltage which would reduce the fog level to less than 1.0 PD, and lengthen the exposure to that of film which would result in the minimum test object density being greater than 2.0 PD. This technique produced a perfectly acceptable image and implied that the eraser could potentially be simplified, and that the system as a whole may be more flexible than anticipated.

4.0 ECONOMIC ANALYSIS

According to one operational source, an F-15 fighter wing with 70-75 aircraft will, on the average, perform about 9 phase inspections per month and spend approximately $3,600 for chemicals in one year. These inspections consist of the following:

200 hr inspection = 116 pieces of film
400 hr inspection = 318 pieces of film
1200 hr inspection = 336 pieces of film

6 ea.	200 hr,	696 film @ $4.50 ea.	= $3,132
2 ea.	400 hr,	636	$2,862
1 ea.	1200 hr,	336	$1,512
9		1668 film	$7,506 x 12 months = $90,072
			+ $3600=$93,672/yr

Discussions were also held with a second operational source. Of all the radiography inspections in the -36, they identified which ones are done at each of the 200 hr., 400 hr., and 1200 hr. phase inspections. These are included in the attached spreadsheets. A 400 hr. inspection will include those inspections listed for the 400 hr. as well as those listed for the 200 hr. inspection. Also, a 1200 hr. inspection will include those listed under the 200 hr., 400 hr., and 1200 hr. inspections.

If it is again assumed that a 70 -75 aircraft wing will perform about 9 phase inspections a month, and the number of film for each of those inspections is calculated from T.O. 1F-15A-36:

200 hr inspection = 396 pieces of film
400 hr inspection = 532 pieces of film
1200 hr inspection = 678 pieces of film

6 ea.	200 hr,	2376 film @ $4.50 ea. =	$10,692
2 ea.	400 hr,	1064	$ 4,788
1 ea.	1200 hr,	678	$ 3,051
9		4118 film	$18,531x 12 months = $222,372
			+ $3600 = $225,972/yr

Even if considering only the conservative case, it is clear that there is significant benefit to be gained by being able to replace film radiography with digital methods. Again, assuming the conservative case, if a system could be acquired for approximately $150,000 then it would be paid for in 1.5 years. Further discussions will be held with various field units in an attempt to resolve the conflicting estimates.

5.0 CONCLUSIONS

a. While the environments are different, filmless radiography (storage phosphor) technology has application to both depot and operational situations.
b. The current technology is adequate for inspection of FOD, moisture entrapment, corrosion, and some cracks. This amounts to approximately 80-85% of routine F-15 inspection needs. Results of these test reinforced confidence in earlier estimations that the RADView filmless radiography system seems to be adequate for FOD and moisture entrapment inspections but, while capable of detecting cracks, it is not yet as sensitive as conventional film. Current work seems to indicate that the current phosphor screens are approximately comparable to Kodak AA film for crack detection.

c. A typical F-15 wing (approximately 70-75 aircraft) will experience an ROI of less than two years.

d. System has also demonstrated potential in the inspection of composites and electronic components.

6.0 RECOMMENDATIONS

a. Development of better resolution and sensitivity in order to achieve an image quality comparable to that being obtained with currently used film. (This task is being performed under ManTech contract # F33615-97-C-5122.)

b. Development of 14"x17" image format (This task is being performed under ManTech contract # F33615-97-C-5122.)

c. Improvement of system throughput - eraser efficiency/speed (being done under ManTech contract)

d. Conversion of film techniques to phosphor (filmless) techniques (calibration, etc.)

e. Development of operational procedures

f. Educational material is needed to aid engineers and technicians in understanding the applicability and benefits of applying filmless radiography.

g. Desire to capture specific frames of real time inspections and store on RADView

h. Understanding of Image Compression Issues

i. Electronic transmission of data/images

j. Improvement in hardware reliability (periodic maintenance)

k. Improvements in software reliability (software coming with v2.0, hardware needs work)

l. Examine applicability to other weapon system and applications (e.g., solid rocket motors, electronics, etc.)